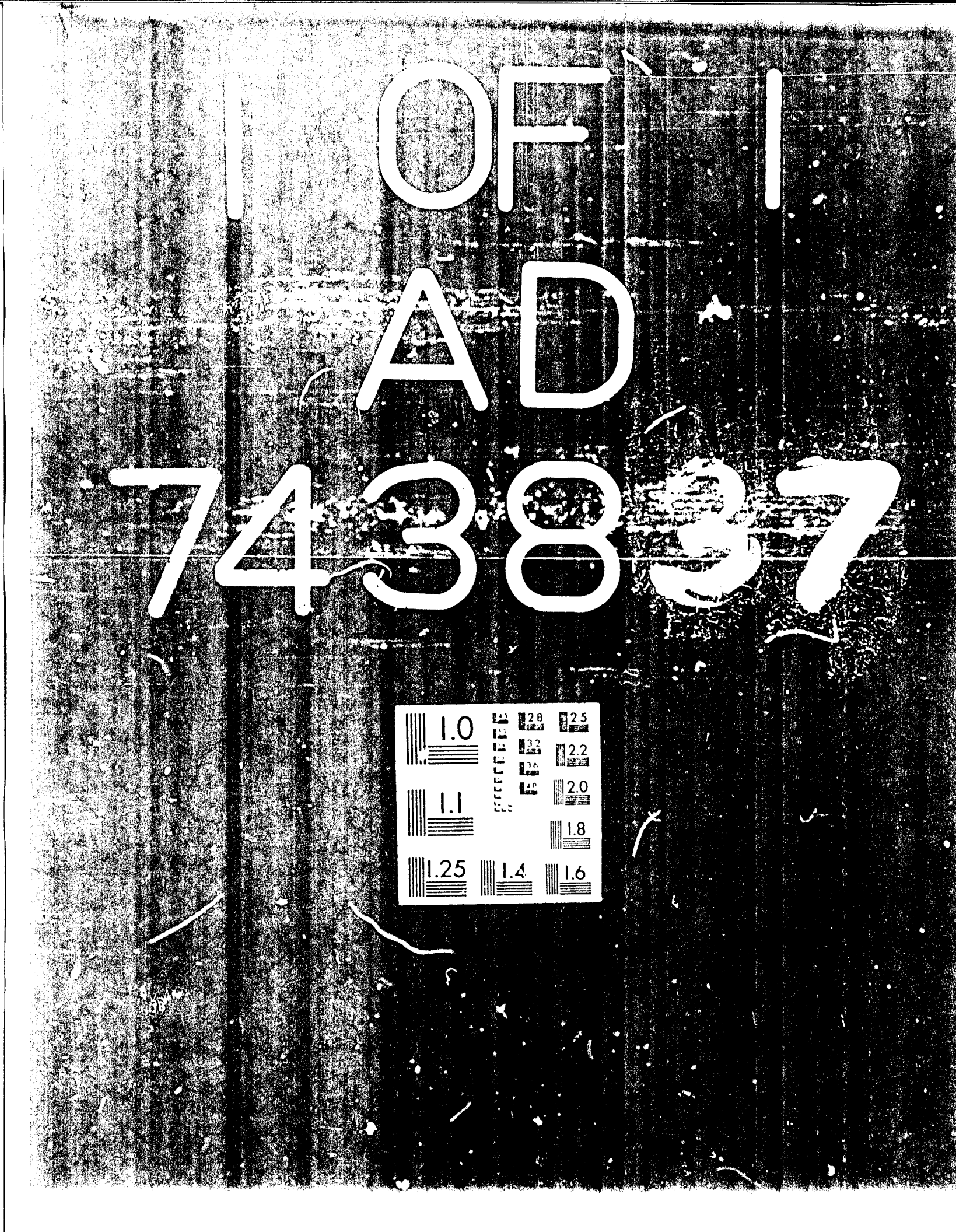
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Columbia University
Palisades, New York 10964

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13. ABSTRACT

Seismological research supported by Air Force contract F19628-71-C-0245 at the Lamont-Doherty Geological Observatory is summarized for the period 1 July 1971 to 31 December 1971. During this period extensive analysis was done on the systematic regional variations in stresses. High stress earthquakes that usually exhibit anomalously large high-frequency content are the most likely ones to be confused with explosion signals. Higher stresses are expected to be accumulated in regions where new faults are being created in competent rocks. A possible temporal change of travel time is observed at some of the stations in western United States that may have been, at least in part, attributed to a change of the stress conditions along the path. The use of 40-second, rather than 20-second, surface wave amplitudes for m_b-M_s graphs was shown to have some distinct advantages for purposes of detection and discrimination. The pronounced difference in spectral content of P waves from earthquakes and underground nuclear explosions suggests a method for identification that is applicable for explosions large enough to be recorded by long-period seismographs at teleseismic distances. This method may be particularly important when long-period instruments are disturbed by other events, and methods of identification that rely on analysis of surface waves become inapplicable.

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Strike-slip					
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by

Tosimatu Matumoto

Lamont-Doherty Geological Observatory
Columbia University
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CONTRACT NO. F19628-71-C-0245

Project No. 1795
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ABSTRACT

Seismological research supported by Air Force contract F19628-71-C-0245 at the Lamont-Doherty Geological Observatory is summarized for the period 1 July 1971 to 31 December 1971.

During this period extensive analysis was done on the systematic regional variations in stresses. High stress earthquakes that usually exhibit anomalously large high-frequency content are the most likely ones to be confused with explosion signals. Higher stresses are expected to be accumulated in regions where new faults are being created in competent rocks.

A possible temporal change of travel time is observed at some of the stations in western United States that may have been, at least in part, attributed to a change of the stress conditions along the path.

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MAJOR SCIENTIFIC ACCOMPLISHMENTS

In the following paragraphs, scientific accomplishemnts are summarized following the itemization in the statement of work of this contract.

Line - Item 1a

Operation of the world-wide Lamont-Doherty network of long- and intermediate-period seismic stations at the Palisades (PAL), Sterling Forest (SFO), and Ogdensburg (OGD) continued during the present contract period.

Line - Item 1b

1. During the last period, a study of earthquakes with anomalously large high-frequency content was begun. These events are of special interest because they are the most likely ones to be confused with explosion signals. High-frequency earthquakes are also called high stress earthquakes because high stresses in the source region are the most likely cause for relatively strong high frequency content.

Before the discrimination problem for individual high stress events is attacked, we must recognize these events and we may ask whether there are systematic regional variations in the stresses. Higher stresses are expected to be accumulated in regions where new faults are being created in competent rocks. Low stresses may prevail along well developed active faults. The simplest method to recognize high stress events is to classify earthquakes by the ratio of a high frequency to a low frequency amplitude. A more sophisticated method is to obtain the body wave spectrum of an earthquake over approximately two decades of frequency and determine the stress-drop.

2. A paper by Molnar and Wyss in which stress-drops of shallow earthquakes in the Tonga-Kermadec arc were determined from displacement spectra of body waves was submitted to Physics of the Solid Earth. They analyzed 37 events and found that earthquakes with the highest stress-drops occurred outside the main thrusting zone. They concluded that the high stress-drop events (high-frequency risk) reflected deformation within one plate of lithosphere and that these earthquakes may have created new faults. Molnar and Wyss studied 18 earthquakes with depths greater than normal in the same area and found that earthquakes of intermediate depth had higher stress-drops than shallow ones. This observation corroborated the results by Tsujiura (1969) and Wyss (1970) who both found marked increase in high-frequency content for earthquakes with increasing depth.

3. A paper entitled "The use of body-wave spectra in the determination of seismic source parameters" by Hanks and Wyss was submitted to the Bulletin of Seismological Society of America. Teleseismic determination of body-wave (P, S) spectra, interpreted in terms of the Brune (1970) seismic source model, are used to estimate the parameters, seismic moment, and source dimension for three large, shallow, strike-slip earthquakes occurring on nearly vertical fault planes and for which the same parameters can be determined from field data. These earthquakes are the Borrego Mountain, California, earthquake (April 9, 1968); the Mudurnu Valley, Turkey, earthquake (July 22, 1967); and the Dasht-e-Bayaz, Iran, earthquake (August 31, 1968). A minimum estimate for the radiated energy is low by a factor of 3-10 with respect to the estimate obtained from energy - magnitude relations for these three earthquakes. The stress drops of these events are of the order of 10 bars.

The above studies underline the importance of exact depth determinations for more or less shallow earthquakes. The deeper an event the more high frequencies will be radiated and the more difficult will it be to discriminate it from explosions. The second conclusion from the above studies is that in an average sense there are regional differences in the high frequency content. However, high-stress regions produce occasionally low-stress earthquakes and vice versa.

4. A paper entitled "Seismic body waves in the vicinity of Mount Katmai, Alaska, and evidence for the existence of molten chambers" by Tosimatu Matumoto was published in the Bulletin of the Geological Society of America. The study revealed the disappearance of shear waves along certain paths crossing the volcanic range. A close geographical correlation of these paths with active volcanoes strongly suggests that magma or zones of partial melting exist and are responsible for S-wave shadowing. By the use of the high attenuation of high-frequency P waves, an estimate of viscosity in a magma chamber of 10^8 cgs units is made.

5. A detailed mapping of the attenuation properties of the wedges of mantle behind island arcs and above the descending lithospheric slabs is currently under way. In this study pP and P waves from intermediate and deep earthquakes as recorded on the WWSSN seismograms were used. Preliminary results strongly confirm the existence of the high-attenuation zone behind the Tonga-Kermadec arc as found by Barazangi and Isacks (1971). A study of all the Earth's island arcs and island arc-like structures is being carried out.

6. An algorithm has been developed to calculate difference formulae for boundary and interface conditions arising in the solution of the elastic wave equation by finite difference methods. Using the calculated formula for the corner of a quarter space, a Rayleigh wave was propagated around the corner. Agreement with model experiments was within the computational error. A similar experiment was performed for a three-quarter space and agreement was obtained with the few published values. The algorithm can be used for any model whose boundaries and interfaces can be approximated by straight lines such as wedges, imbedded material, surface elevations, etc.

7. The elastic waves radiated by a stress-free surface, which grows within a pre-stressed medium was made. Earthquakes may reasonably be modeled in this way, and, for cases with an elliptic fault plane, the radiated waves can (surprisingly) be calculated by Cagniard-de Hoop theory. A simple method has also been found to obtain the far-field pulse shape from given motions on the fault plane.

8. A study is being conducted to find the initial phase patterns associated with azimuth for nuclear explosions at NTS and nearby natural events. Long-period WWSSN Rayleigh wave data is used to calculate the initial phase patterns. It is hoped that a specific phase relation can be used in discrimination-detection work.

Line - Item 1c

1. A paper of focal mechanisms for shallow earthquakes occurring from 1964 to June, 1969, in the region from New Guinea to the New Hebrides titled "Focal mechanisms and plate tectonics of the southwest Pacific" by Johnson and Molnar was submitted to the Journal of Geophysical Research. Ninety-six new focal mechanisms were determined for earthquakes on the belt of seismic activity separating the Pacific and Australian plates. The direction of convergence of these plates varies from NE-SW to east-west. The Australian plate underthrusts the Pacific plate to the ENE under the Solomon and New Hebrides Islands, and overthrusts the Pacific to the east along the Tonga-Kermadec arc and North Island of New Zealand. Between the southern part of the New Hebrides arc and the northern end of the Tonga arc, several mechanisms are consistent with a zone of transform faulting between the arcs, but the tectonic boundary in this area is clearly more complex than a simple transform fault. The data for the Macquarie Ridge concur with the idea that the pole of rotation for the Pacific and Australian plates is nearby and to the east of this feature. The data also suggest a NNE-SSW convergence of the Pacific plate and the Australian plate in northwestern New Guinea.

2. A paper entitled "Earthquake fault parameters and tectonics in Africa" by Maasha and Molnar has been submitted to the Journal of Geophysical Research. Fault plane solutions of earthquakes in southern Africa indicate that the least compressive stress is oriented approximately east-west nearly parallel to that in the northern part of the rift system. Seismic moments, source dimensions, and stress drops were determined for eight earthquakes from body and surface wave spectra using the theory of Brune (1970). Spectral estimates of these quantities for the 1966 earthquake in

the Republic of Zaire agree well with those observed in the field. Relatively higher stress drops are found for events not associated with rift faulting. If higher stress drops indicate higher rock strength, then these, with other geological and geophysical data, suggest that the northern part of the rift system is similar to ocean ridges and behaves as a plate boundary, but the southern part is different and is not a plate boundary. The tectonics associated with the northern part of the rift system appear to migrate southwards.

Line - Item 1d

A paper entitled "Mantle wave analysis by a phase-equalization-and-sum-method for the Montana LASA long-period data" by Kazuo Hamada was published in the Bulletin of the Seismological Society of America. A paper entitled "Mantle Rayleigh waves for shield, oceanic, and tectonic areas using LASA long-period data" by Kazuo Hamada was submitted to the Journal of Geophysical Research.

By using LASA long-period digital data and high-gain digital data at Ogdensburg, New Jersey, group velocities of mantle Love and Rayleigh waves were determined by means of a recently developed new method. Combining these group velocities with Kanamori's phase velocity data, regionalized shear-velocity models of the upper mantle were inferred. Important conclusions are: a. Shear velocity differences among the different tectonic regions exist at depths less than 300 km. b. Shear velocities in the upper mantle are obviously higher for the shield areas and lower for the tectonic areas than those for the oceanic areas; the velocity difference between the shield and tectonic models is approximately 10% at depths less than 100 km, decreasing gradually; 5% at a depth of 200 km. c. The shield data do not require a strong low velocity channel in the upper mantle like the oceanic model. d. The tectonic data do not necessarily require the presence of high velocity lid just beneath M-discontinuity. e. The oceanic data require obviously a strong low velocity channel in contrast with the other two models. f. The dispersion of Love and Rayleigh waves for the tectonic regions can be explained well by the different shear velocity structures rather than by the same one; the shear velocities expected from Love waves are higher than those expected from Rayleigh waves by 0.2 km/sec. The velocity differences are concentrated at depths from 150 to 300 km. This discrepancy requires anisotropy or an equivalent laminar-melting structure.

Line - Item 1e

1. A paper entitled "Microseismicity and tectonics of the Nevada seismic zone" by Frank J. Gumper and Christopher Scholz was submitted to the Bulletin of the Seismological Society of America. Microseismicity, composite focal-mechanism solutions, and previously published focal parameter data are used to determine the current tectonic activity of the prominent zone of seismicity in western Nevada and eastern California, termed the Nevada Seismic Zone. The microseismicity substantially agrees with the historic seismicity and delineates a narrow, major zone of activity that extends from Owens Valley, California, north past Dixie Valley, Nevada. Focal parameters indicate that a regional pattern of NW-SE tension exists for the western Basin and Range and is now producing crustal extension within the Nevada Seismic Zone. An eastward shift of the seismic zone along the Excelsior Mountains and left-lateral strike-slip faulting determined from a com-

posite focal mechanism indicate transform type faulting between Mono Lake and Pilot Mountain. Based on these results and other data, it is suggested that the Nevada Seismic Zone is caused by the interaction of a westward flow of mantle material beneath the Basin and Range Province with the boundary of the Sierra Nevada batholith.

2. A paper entitled "P-wave spectra from underground nuclear explosions" by Peter Molnar was submitted to the Geophysical Journal of Royal Astronomical Society, London. This paper reports observations of P-wave spectra from underground nuclear explosions for periods greater than about 1 s. The spectra have a maximum at about 2-3 s and decrease rapidly at longer periods. Two phenomena could cause such a decrease: (1) The surface reflection (pP), with its polarity opposite to that of the direct P wave, might differentiate the long-period signal and cause a modulation of $2|\sin\omega t_o/2|$ where t_o is the interval of time between P and pP; or (2) the source time function for the pressure on the boundary of the elastic zone surrounding the explosion might more nearly resemble an impulse than a step function as often assumed. The data are consistent with the simultaneous occurrence of both phenomena, but they are of insufficient quality or quantity to establish which is more important. If other information shows that the reflection does not have a large effect on the observed spectrum, then the data show that the source time function is primarily an impulse.

In addition, the pronounced difference in spectral content of P waves from earthquakes and underground nuclear explosions suggests a method for identification that is applicable for explosions large enough to be recorded by long-period seismographs at teleseismic distances. This method may be particularly important when long-period instruments are distrubed by other events and methods of identification that rely on analysis of surface waves become inapplicable.

3. A paper entitled "Excitation of seismic surface waves with periods of 15 to 70 seconds for earthquakes and underground explosions" by J. Savino, L. R. Sykes, R. C. Liebermann, and P. Molnar was published in the Journal of Geophysical Research. Using data from high-gain seismographs operating in the deep (543-meter) mine observatory at Ogdensburg, New Jersey, we analyzed the excitation of long-period surface waves by earthquakes and underground explosions for four different regions of the world: western United States, the Aleutians, Novaya Zemlya, and central Asia. The most important result of this study is that discrimination between earthquakes and underground explosions on an M_S-m_b basis is enhanced when the amplitudes of Rayleigh waves with periods near 40 sec, rather than 20 sec, are used to determine M_S. A discriminant based on surface waves with periods near 40 sec is particularly advantageous because of a very stable and pronounced minimum in earth noise in this period range. Love waves also yield a distinct separation between earthquakes and explosions on the basis of M_S (Love) at 20 and 40 sec with m_b, and can be used for discrimination of small events for which no Rayleigh waves are recorded. The discrimination threshold at Ogdensburg is $m_b' \approx 3.8$ for the western United States at a distance of about 30° and $m_b \approx 4.4$ for the Aleutians at 70°. All the events studied could be discriminated by using 40-sec Rayleigh waves. Amplitude spectra of Rayleigh waves in the period range 15 to 70 sec were computed for events in the western United States, the Novaya Zemlya region,

and the Aleutians. The spectral amplitudes decrease more rapidly with increasing period for explosions than for earthquakes in the western United States and Novaya Zemlya. These spectral differences are consistent with an impulsive source time function for explosions. In the Aleutians, however, the shape of the spectrum of long-period waves for the underground explosion Milrow is similar to spectral shapes for some, but not most, nearby earthquakes. Two plausible explanations for this spectral similarity are contamination of the Milrow spectrum by earthquake-generated Rayleigh waves, or the effects of focal depth and radiation pattern on the earthquake spectra.

4. A study on a temporal change of the travel time observed from the underground nuclear explosions has been continued to utilize the accurately established location and origin time of these events. The travel times measured at a station for the repeated explosions from the Nevada Test Site show a fluctuation of as great as over 1 second. This fluctuation of the travel time is primarily resulted from an emergent onset of the wave and from unproper identification of phases. By eliminating some of the events with smaller yield, the fluctuation is greatly reduced. Difference of the distance, depth, and subsoil condition near the station also contribute to the fluctuation of the travel time. Some of the high quality stations (with low ground noise and with accurate time marks) show consistent travel time, and their temporal changes can be examined. At the stations MHC(Mt. Hamilton, California) and KNUT (Kanab, Utah), it is observed that the travel time decreases as the seismic activity near the station increases and the travel time increases rather abruptly when the seismic activity halted. At the most of the stations, however, the relation between the localized seismic activity and travel time is rather complicated. This complication implies that the physical condition at intermediate depths that has not been reflected to the seismic activity at shallower depths may play an important role on the temporal change of the travel time.

Line - Item 1f

1. A paper entitled "Three-dimensional seismic ray tracing in a laterally heterogeneous spherical earth" by Klaus H. Jacob was published in the Journal of Geophysical Research. Recent seismological studies suggest lateral inhomogeneities in P and S velocities of the mantle that are associated with slabs of mobile lithosphere descending into the mantle beneath island arcs. In special cases, travel times of P traversing such zones can differ by as much as 5 sec and of S by up to 10 sec from standard travel times. In addition, such zones are characterized by relatively low attenuation of S-wave energy compared with high attenuation in a broad zone on the landward side of the active volcanoes. To explain the observed anomalous travel times and attenuation phenomena, it is necessary to trace the path of body waves through laterally heterogeneous earth models. The technique of ray tracing developed here uses Fermat's principle to obtain the differential equation of a ray in spherical coordinates. The position, direction, and travel time of the seismic wave front at any point along the curved ray path are obtained by numerical integration of the differential equation for an assumed three-dimensional, continuous velocity distribution.

The problem of representing a realistic three-dimensional velocity structure in the earth is solved in a way that is especially suitable for use on computers. Some examples for rays traversing an island-arc structure are presented. The implications of this method of tracing rays in a laterally heterogeneous earth are discussed with respect to seismic travel-time studies, interpretation of residuals in terms of tectonic heterogeneities, source bias, and the precise location of earthquakes and nuclear explosions; $dT/d\Delta$ measurements from large seismic arrays and their inversion to obtain details of the velocity structure in the upper mantle are also discussed.

2. A paper entitled "Seismic waves reflected from velocity gradient anomalies within the Earth's upper mantle" by Paul G. Richards has been submitted to Zeitschrift für Geophysik. Classical Thomson-Haskell methods have recently been extended, to obtain the asymptotic wave solution in a stratified elastic medium which has both first and second order discontinuities in the elastic parameters. These methods are used here in a discussion of the observed precursors to seismic waves P′P′. The frequency-dependent reflection coefficient R (= reflected/incident displacement amplitudes) is calculated for several models of transition regions in the Earth's mantle. To generate observable precursors to P′P′, by reflection from horizontal layering within the mantle, the thickness L of the region of transition is shown to be much smaller than has generally been supposed. This result follows from the rapid decrease in R as the transition thickness increases from zero to one wavelength. For example, R(1 second) > 2 1/2 % only if L < 4 km., even in cases of 10% total changes in velocity.

LIST OF PERSONNEL

Scientists:

L. A. Alsop (N/C)
K. Hamada
T. Matumoto
P. Molnar
J. Oliver
P. G. Richards
J. M. Savino
L. R. Sykes
M. Trifunac

Graduate Students:

Y. Aggarwal
V. Cormier
T. Fitch
S. Gregersen
F. Gumper
T. Johnson
M. Sbar

Engineers:

F. England
G. Hade

Problems Encountered

None

Fiscal Status

Estimated expenses through the close of the present contract period:	$ 96,118.42
Total cost to completion of contract:	278,316.00

Action Required by the Government

None

Future Plans

Future plans call for the continuation of the research outlined above and in other areas specifically related to the VELA-UNIFORM program.

Scientific Papers

Aggarwal, Y. P., M. Barazangi, and B. Isacks, Pn, Sn travel times in the Fiji-Kermadec region: a zone of low velocity behind the Tonga arc, in preparation.

Gumper, F. J., and C. Scholz, Microseismicity and tectonics of the Nevada seismic zone, Bull. Seism. Soc. Amer., 61, 1413-1432, 1971.

Hamada, K., Mantle wave analysis by a phase-equalization-and-sum-method for the Montana LASA long-period data, Bull. Seism. Soc. Amer., 61, 875, 1971.

Hamada, K., Mantle Rayleigh waves for shield, oceanic, and tectonic areas using LASA long-period data, submitted to J. Geophys. Res.

Hamada, K., Regionalized shear-velocity models for the upper mantle inferred from surface-wave dispersion data, in preparation.

Hanks, T. C., and M. Wyss, The use of body-wave spectra in the determination of seismic source parameters, submitted to Bull. Seism. Soc. Amer.

Jacob, K. H., Three-dimensional seismic ray tracing in a laterally heterogeneous spherical Earth, J. Geophys. Res., 75, 6675-6688, 1970.

Johnson, T., and P. Molnar, Focal mechanisms and plate tectonics of the southwest Pacific, submitted to J. Geophys. Res.

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Matumoto, T., Seismic body waves observed in the vicinity of Mount Katmai, Alaska and evidence for the existence of molton chambers, Bull. Geol. Soc. Am., 82, 2905-2920, 1971.

Molnar, P., P-wave spectra from underground nuclear explosions, Geophys. J. Roy. Astr. Soc., 23, 273-286, 1971.

Molnar, P., and M. Wyss, Moments, source dimensions, and stress-drops of shallow earthquakes in the Tonga-Kermadec arc, Physics of the Solid Earth, submitted, 1971.

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S. Gregersen
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T. Johnson
M. Sbar

Engineers:

F. England
G. Hade

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